Control and Balancing of Two-Wheeled Mobile Robots using Sugeno Fuzzy Logic in the domain of AI Techniques

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Abstract — A comprehensive research has been addressed in the current analysis towards the control and stability of two-wheeled mobile robots using Sugeno Fuzzy logic technique. During the analysis, several inputs such as tilting angle, current acceleration and current velocity and outputs such as final acceleration and final velocity are calculated to make the two-wheeled mobile robot stable during navigation. In the process, a theoretical, as well as experimental results, are given to prove the authenticity of the methodology adopted. It is observed that theoretical results agree well with the experimental results. It is also corroborated that Takagi Sugeno method can be used effectively for control of two-wheeled robots. In the process, several other AI techniques are also analyzed. A sincere effort has been made for fruitful use of different AI techniques for control of two-wheeled robots.

Index Terms— AI techniques, Fuzzy, Takagi Sugeno, Two-Wheeled Robots, Stability.

1 Introduction

In the past decade, two-wheel self-balancing robot has got an attention of researchers because of its inherently unstable characteristic. During 90's, the inverted pendulum was only the inspiration for researchers to research on it [1, 2]. To make it stable a suitable controller can be designed using various AI techniques, such as neural network control, fuzzy logic control etc. [3-6]. Two wheel robots are increasingly found everywhere used as a vehicle for covering short distances in large scale industries, for entertainment, for transportation of goods and for quick maneuvering. It's one of the biggest advantages is, it can turn with zero turning radius which enhances its utility in complex platforms which is given by Grasser et al. [7]. The wheels are arranged coaxially and said to be unbalanced when the center of mass lies above the axis of wheels which can keep balance based on control algorithm using sensory data. The objective is to maintain the tilt angle using a suitable control algorithm. This task requires an accurate measurement of altitudes of the robot using multiple sensors [8-10]. The control algorithm is designed using Takagi Sugeno Fuzzy logic approach. Sensors like accelerometers and gyroscope are integrated into circuits which are used for tilt measurement [11].

2 Inside View of AI Techniques for E0ffective use Control for TWMR

The stability issue of two wheeled robot leads researchers to work on it. In this section, a decent study and systematic comparison is done between various AI techniques like neural network, Fuzzy logic etc. Ha et al. [2] have worked on controlling as well as navigating the inverted pendulum. Experimental verifications is done using robot "Yamabico Kurara". Sun et al. [3] proposed LQR controller contained a neural network in it. The quality of optimality of LQR controller helps in fast convergence of neural network outputs. In papers [6, 12-21], T-S Fuzzy controller have been implemented with different membership functions. In papers [6, 23] balancing of TWMR as well as motion control both are done. Yong et al. [6] used Fuzzy controller and parallel distribution compensator (PDC) which control the balance and motion control both. Wu et al. [13], have compared pole placement feedback controller and fuzzy controller and found best results with fuzzy controller. A satisfactory responses are recorded on a flat as well as inclined terrains in paper [16-17]. It has been found experimentally that Fuzzy controllers are more robust then linear controllers, [17]. In Li et al. [19] wheels are coaxially coupled. Papers [22-24] have proposed adaptive Fuzzy control algorithm for balancing of TWMR. Papers [25-35] discuss use of Fuzzy logic in various scenarios towards control of robots and subsequent path planning, in some of the papers comparisons are done between fuzzy controller and linear or non-linear controller in order to prove the higher performance of Fuzzy controller. Papers [36-42] use the hybrid fuzzy controller in which fuzzy logic is applied by considering continuous system as well as a discrete system. Papers [43-65] discuss various membership functions and their applications. MATLAB simulation are done using Fuzzy logic in paper, [67]. The fuzzy control algorithms are divided as Takagi Sugeno, Mamdani [69] and Type 2 fuzzy [60-72]. An artificial neural network is an approach which is inspired by the biological neural network i.e. animal brain. Papers [73-104] discuss about artificial neural network approach, it is implemented for balancing TWMR [73-78], for navigation of mobile robot [79-90] and for other engineering analysis [91-94]. According to the law of the adaption, every adaptive system converges to a state in which all kind of stimulation ceases. Papers [95-107] discuss about various neural network techniques such as back propagation and RBFNN techniques for handling of mobile robots in unknown environment. Adaptive technique is merged with neural network approach in papers [73, 74, 78, and 104]. Sometime inputs of fuzzy controller are developed from the output of neural network, called as neuro-fuzzy technique which are discussed in the papers [108-120]. In most of the cases neuro fuzzy system is 3 layered neural network. Input variables are put in first layer, hidden layer shows the fuzzy rules and output variables are shown by third variable. The adaptive neuro fuzzy inference system (ANFIS) is a technique in which combined effect of adaptive neural network and fuzzy logic is observed which is discussed in papers [121-141]. If- Then Fuzzy rules are implemented which has capability of approximating a nonlinear function. In papers [142-146] multiple ANFIS (MANFIS) is discussed. Papers [147- 150] discuss the idea of implementation of hybrid techniques.

The Genetic algorithm is a techniques which is inspired by natural selection which comes under evolutionary algorithm. The optimization of solutions using Genetic algorithms are done and very common now a days, which is mainly inspired by biological operators such as crossover, mutation and selection. Papers [151-182], discuss about the implementation of various genetic algorithm for purpose of self-balancing [151-153]. Sahu et al. [155] have compared the DE algorithm with genetic algorithm. The navigation of mobile robots are discussed using GA in papers [157-173]. The differential evolution (DE) algorithm is useful for optimization by considering large space of candidate [72, 154, 156, 168, and 169]. DE algorithm does not restrict the solution by considering very less assumption. Some of the bio-inspired techniques such as Gravitational Search Algorithm (GSA), Simulated Annealing (SA) and Particle Swarm optimization (PSO), Ant colony, Immune system, Invasive weed optimization, Bee colony, Firefly algorithm, Cuckoo search, Frog leaping algorithm are most commonly used algorithms for optimization some of them are discussed in papers [174-178]. Panigrahi et al. [179] gives a comparison between Gravitational Search Algorithm (GSA), Particle Swarm optimization (PSO) and Simulated Annealing (SA) and observed that GSA controller performs better than SA and PSO. Papers [180-190] discuss on Harmony search method, frog leaping algorithm, Flower Pollination algorithm (FPA) for control of wheeled mobile robots. Artificial Immune System and its applications in mobile robots for navigational purpose has been described in papers [191-197]. Cuckoo search is a potential optimization method for solving various engineering problems and robot path planning problem and is elaborated in papers [198-203]. Kinematic analysis of robots plays a vital roles during robot navigation and is addressed in papers [204-215]. Papers [216-224] focus on gravitational search, harmony search and AI techniques for various engineering problems and self balancing and control of wheeled robots.

So, AI techniques are efficient for balancing and navigation of mobile robot. Some of the hybrid techniques make it more efficient. Between Fuzzy logic, neural network and genetic algorithm large combination is found between neural network and fuzzy logic (neuro fuzzy controller) due to its fast convergence towards the optimum solution.

3 Analysis of TWMR using Takagi Sugeno Fuzzy logic

The research discussed in this paper mainly comprises of stability of TWMR. The zero order Takagi Sugeno Fuzzy inference technique has explored for balancing and motion control of TWMR. The main components of TWMR are actuators, sensors, controller and body. The body of TWMR carries two coaxially arranged wheels, actuators, T-S Fuzzy controller, sensors etc. The inputs to the T-S fuzzy method, are tilt angle (TA), current velocity (CV) and current acceleration (CA). And the outputs to the T-S fuzzy method, are new velocity (NV) and new acceleration (NA). The range of values of tilt angle, velocity and acceleration lie between -21 to +21 degrees, 0 to 10 m/s and 0 to 15 m/s^2 respectively. The Gaussian type membership functions are used as inputs for TA, CV and CA. The range for TA is divided in 5 intervals with the interval value of 10.5 degree. Similarly 5 intervals are considered for velocity and acceleration, the interval values are 2.5 m/s and 3.75 m/s^2 respectively. Total number of possible Fuzzy rules are m^n (where m is number of variable in each fuzzy sets and n is number of inputs) which implies 5^3 =125. Total 125 Fuzzy rules are introduced and evaluated for the analyses. The Fuzzy membership functions for inputs (TA, CV, and CA) are graphically shown in Figs 1-3 respectively. For execution of Fuzzy control, mainly four steps are introduced i.e. (i) Fuzzification, (ii) Fuzzy Rule evaluation, (iii) Aggregation and (iv) De-fuzzification. The Fuzzy sets (Fig. 4) are categorized as {NN, N, Z, P, PP}, {VL, L, M, H, VH} and {VL, L, M, H, VH} for TA, CV and CA respectively.

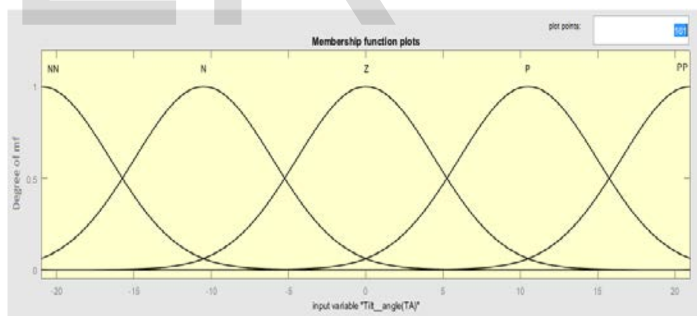

Fig. 1 Input Tilt angle (TA)

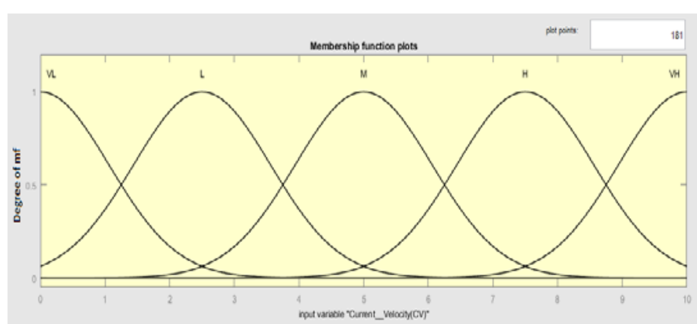

Fig. 2 Input Current Velocity (CV)

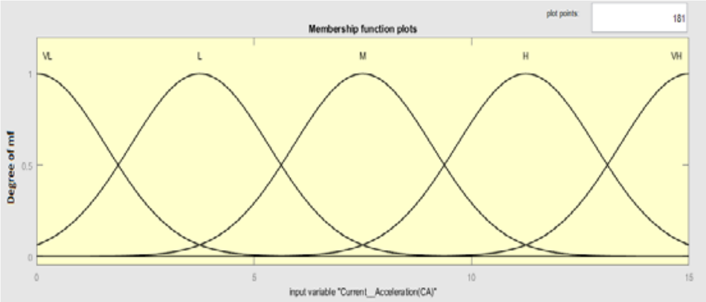

Fig 3 Input Current Acceleration (CA)

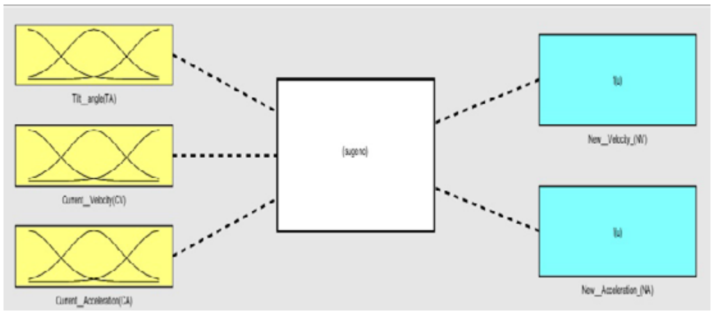

Fig. 4 Fuzzy inference system (FIS)

3.1 Membership function and Fuzzy Rules

The Gaussian Membership Function is given as,

$$\mu_d(x_{ij}) = \frac{1}{\sigma_{ij}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x_{ij}-\mu_{ij}}{\sigma_{ij}}\right)^2}$$

Where $x_{ij} \in$ (elements of fuzzy sets) where i number of inputs and j is number of elements in each fuzzy sets. Where σ and μ are the parameters of bell shaped curve called as standard deviation and expected value respectively. The parameters of membership function control the shape of curve. The values of the parameters of each elements in all Fuzzy sets are mentioned in Table 1. After fuzzification of inputs, the rules are evaluated which can be expressed in general form:

$$R: If\ (x_1\ is\ x_j) \cap (x_2\ is\ x_j) \cap (x_3\ is\ x_j)\ then\ (y_1\ is\ y_j) \cap (y_2\ is\ y_j)$$

Where, y_1 is New Velocity (NV) and y_2 New Acceleration (NA). The aggregated outputs of NV and NA is given as,

$$y_1 = \frac{\sum_{i=1}^{i=3} w_i^{(1)} \times y_{ij}}{\sum_{i=1}^{i=3} w_i^{(1)}}$$

and

$$y_2 = \frac{\sum_{i=1}^{i=3} w_i^{(2)} \times y_{ij}}{\sum_{i=1}^{i=3} w_i^{(2)}}$$

Where, $w_i^{(1)}$ and $w_i^{(2)}$ weightage of all inputs (i =1, 2, 3) projected in outputs NV and NA. For AND operation w_i is expressed as,

$$w_i = min\{\mu_d(x_{1j}), \mu_d(x_{2j}), \mu_d(x_{3j})\}$$

TABLE 1
THE VALUES OF STANDARD DEVIATION AND EXPECTED VALUE FOR MF OF EACH ELEMENTS OF FUZZY SETS

S. No. (j)	Set of TA (i=1)	σ_{1j}	μ_{1j}	Set of CV (i=2)	σ_{2j}	μ_{2j}	Set of CA (i=3)	σ_{3j}	μ_{3j}
1	NN	4.46	-21	VL	1	0	VL	1.6	0
2	N	4.46	-10.5	L	1	2.5	L	1.6	3.75
3	Z	4.46	0	M	1	5	M	1.6	7.5
4	P	4.46	10.5	H	1	7.5	H	1.6	11.25
5	PP	4.46	21	VH	1	10	VH	1.6	15

4 DESCRIPTION OF TWO WHEELED MOBILE ROBOT

The two wheeled mobile robot contains intermediate wheels. These wheels are co-axially aligned and independently mounted on body is shown in Fig. 5. Each wheel is driven by DC servo motor (High Torque DC Geared Motor 300 RPM). The attitude estimation of the TWMR's posture can be attained by the MPU 6050 sensor. The raw sensory information from the tri-axis accelerometer and gyroscope is filtered by the implementation of complimentary filter equations. Now the sensory data is feed to the microcontroller board (Arduino UNO ATmega 328). The microcontroller generation the required torque command and sends the signal to PWM (Pulse Width Modulation) generator for the actuation of DC motor. The structure of body contains four studs and three carriers (wooden rectangular plates) with two holes. The lower carrier carries microcontroller board and sensor board. Below lower carrier DC motors are assembled with rigid joints.

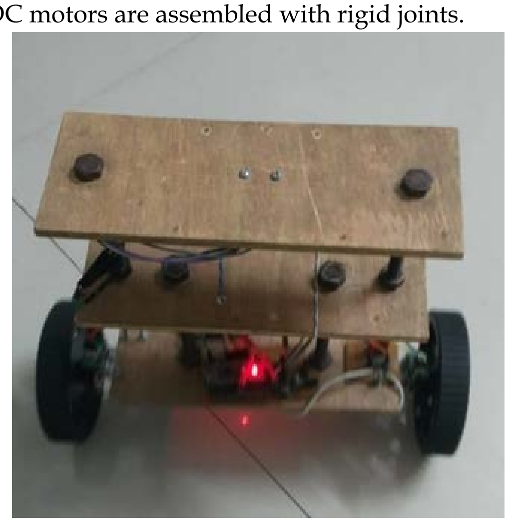

Fig. 5 Two wheeled mobile robot (TWMR)

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4 Comparison of Experimental and Simulation Results of Two Wheeled Mobile Robot

The experimental setup is developed in the lab, from which velocity and accelerations are recorded for any 10 instants and expressed in tabular form in Table 2. Simulation results are done on MATLAB Simulink. Fuzzy controller is modeled in MATLAB toolbox. The fuzzy controller is inserted in Simulink model. The results are noticed for same inputs as done in experimental setup. The results are compared and percentage error is calculated and error is found to be within 10%.

TABLE 2
Comparison of Outputs

S No	Simulation values		Experimental values		%Error $\left\lvert\frac{NV_S - NV_E}{NV_S}\right\rvert \times 100$	% Error $\left\lvert\frac{NV_S - NV_E}{NV_S}\right\rvert \times 100$
	NV_S (m/s)	NA_S (m/s^2)	NV_E (m/s)	NA_E (m/s^2)		
1	4.703	8.521	4.75	8.6	0.99	0.93
2	9.231	14.131	9.3	14.5	0.748	2.61
3	7.614	11.213	7.8	11.9	2.44	6.12
4	2.736	5.923	2.9	6.3	5.99	6.36
5	3.482	6.925	3.8	7.4	9.13	6.85
6	1.564	2.952	1.7	3.2	8.69	8.40
7	0.571	1.146	0.6	1.2	5.07	4.71
8	6.415	12.932	6.6	13.3	2.88	2.84
9	0.152	0.473	0.167	0.52	0.64	9.93
10	0.055	0.351	0.06	0.32	9.09	8.83

5 Conclusion

A systematic approach has been developed in current paper for solving a problem of instability of TWMR. The non-linearity of system is eliminated by T-S Fuzzy logic controller by taking simple input and output variables. The methodology developed is also been verified and results are tabulated in Table 2. A desirable results are noticed during experiment and simulation, and found within 10%.

In future, other AI techniques will explored for finding out better solution compare to current solution.. Also by increasing the elements of Fuzzy sets we can precise the result.

Nomenclature

Symbols	Description
NN	Very less value of Tilt Angle
N	Less value of input Tilt Angle
Z	Zero value of Tilt Angle
P	Positive value of TA
PP	Highly positive value of TA
VL	Very Low
L	Low
M	Medium
H	High
VH	Very High

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